THE TIME TRAVELER'S CLOCK

The Project's History and User Manual

Euclid Laboratories, Inc. -- Teaticket, MA

The Time Traveler's Clock User Manual

"A Man with a watch knows what time it is. A man with two watches is never sure."
--Lee Segall

"A man with three clocks is more sure than a man with two clocks."
--Tim Van Baak

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GPS Receiver and Clock

The most precise and accurate time signal currently available on Earth is from the global constellations of navigational satellites, such as GPS (US), Glonass (Russia), Beidou (China), and Galileo (European Union). To provide position data to GPS receivers, the satellites contain cesium atomic clocks which are continuously monitored and adjusted by their respective countries. A GPS timing receiver can provide time to within as little as 10 nanoseconds as long as it has at least four satellites in view. When satellite reception is lost, the GPS timing receiver goes into “holdover” mode, in which it uses an internal quartz oscillator to maintain time. In holdover mode a GPS timing receiver by itself can maintain time to within 100 parts per billion, or a few seconds per year.

Cesium Reference

The cesium reference oscillator is known as a “chip-scale atomic clock” (CSAC). In the CSAC, the oscillations of an isotope of cesium provide a “Stratum 1” 10 megahertz reference signal. This signal stabilizes the GPS receiver so that the clock will operate at the highest possible precision when a GPS signal is not present. The cesium CSAC is accurate to $1x10^{-11}$, which translates to less than a millisecond per year.

Silicon Receiver and Clock

An independent electronic clock is incorporated which utilizes a silicon real-time-clock (RTC) chip to provide time in case the GPS signal is unavailable and the CSAC atomic clock fails or runs out of power. The RTC chip contains a temperature-compensated quartz oscillator accurate to within a few minutes per year. The RTC chip will operate independently from all the other systems by means of a lithium cell for several years. It’s time and date are displayed on the display panel, which panel must be powered on, at least temporarily, to read the time).

Hamilton 21 Marine Chronometer

Before the advent of radio time signals and portable quartz clocks, ships at sea utilized a highly precise mechanical clock known as a chronometer to ascertain the ship’s longitude. Chronometers sufficiently accurate to provide navigational time at sea were first developed in the late eighteenth century by John Harrison. Over many years the design of marine chronometers advanced, culminating in the Hamilton Model 21 Marine Chronometer, developed during World War II by the Hamilton Watch Company in Lancaster, Pennsylvania. The Hamilton chronometer was an improvement of chronometers manufactured in Switzerland.

The US Navy and US Army used these chronometers until 1985, when they were replaced by quartz instruments. The Hamilton 21 has a typical rate stability of one part per million, equivalent to less than a minute per year. Generally marine chronometers are provided to the user with data on when it was set to correct time and how much the time can be expected to vary per day (the rate error). For navigational use, the user

must calculate the actual current time using the rate error and the number of days since the chronometer was set to correct time.

The TTC contains a servo mechanism which provides a mechanical twisting motion to the chronometer once per second to keep the chronometer synchronized with the GPS timing receiver (which in turn is stabilized by the cesium CSAC). Thus, the GPS clock, the cesium frequency reference, and the Hamilton chronometer are kept in resonance, and the chronometer will remain as accurate as the GPS and atomic references.

The Hamilton 21 chronometer in the TTC is equipped with an electronic winding system that winds the chronometer each hour to a consistent state of winding.

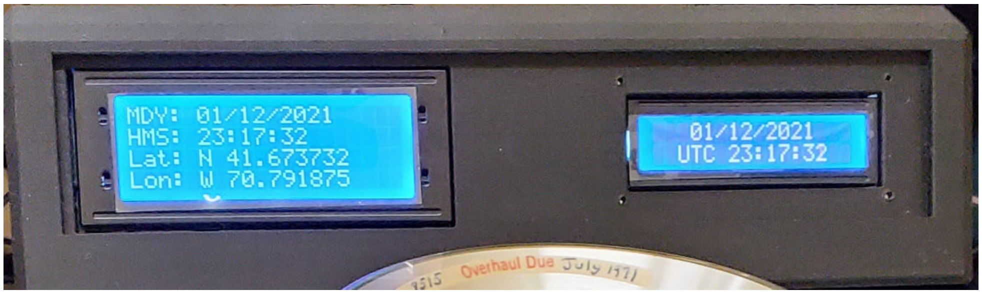
In order that precise time could be calculated from the Hamilton chronometer even if the GPS and atomic references are not functioning (for example, if electrical power has been lost for longer than the backup batteries will maintain operation), the natural rate of the chronometer is measured once per day for a period of thirty minutes (at midnight), and the deviation of the mechanical clock from the GPS and atomic references is measured and printed out on the external printer. The user will thus have the best possible knowledge of the rate error of the chronometer, and the precise navigational time can be calculated from the number of days since it was last synchronized and the average rate error per day.

Figure 1: Hamilton 21 Marine Chronometer

GPS and Silicon Clock Display Panel

The TTC has an electronic display panel which indicates the UTC time, date, latitude, and longitude from the GPS clock as well as UTC time and date as maintained by the silicon RTC clock.

Figure 2: GPS and RTC Display



UTC Navigational Time

There are many standards for time and date. Besides the standard local time zones, there is a basis time known as Coordinated Universal Time (UTC). UTC is defined as the time at the zero meridian which passes through Greenwich, UK. It is regulated by an international committee, the International Time Bureau. Periodically, leapseconds are added (or subtracted) from UTC in order to keep it more or less synchronous with Earth's rotation relative to the stars. Since UTC is always within one half second of the Earth's rotation, it is the preferred time standard to be used for navigation. For that reason, the TTC uses UTC in all its displays and on the Hamilton chronometer.

Origin of the TTC

How Did This Project Begin?

After discovering and rebuilding the Time Viewer originally constructed by Leonardo; da Vinci, the present inventor saw the need for a navigational clock for time travelers. It may be true that Leonardo traveled to America in the 1940s, that he wanted to return to Milano in 1478, and that he built the Time Viewer in order to learn the future technology needed to construct a time-traveling machine. We know that Leonardo did remain in Italy for the rest of his life. Could it be that he couldn't navigate in time anymore, since he lacked a chronometer? If the present inventor is ever able to build a time-traveling machine, he would want to carry with him the most reliable possible chronometer. So, first things first: the inventor turned his efforts to creating that timekeeper.

Figure 3: Leonardo's Time Viewer

Why Do You Need a Time Traveler's Clock?

Imagine you're traveling in time and space. Just like navigators of old, you'll want to have some "bearings" back home, so you can return or go to a new destination. Time will essential to navigation, and we can assume that UTC will always be a good time to know.

But, you never know—you might end up in the past when there was no GPS (the atomic CSAC will keep you navigating); or, you might end up before there was electricity (you can always wind your chronometer manually, and use the printed data to know the corrections you'll need to apply to the time that the chronometer displays). You might travel to a time near the present when you can find electricity, but the GPS system isn't operational. You might travel to the future when the time standards and navigational systems are completely different from what we have now (but you'll be able to find some form of electricity to keep your batteries charged to maintain your GPS internal clock and your atomic-stabilized chronometer.

Eventually, the sands of time may cause the GPS and CSAC systems to fail, but you'll be left with your silicon RTC clock. And, in the end, you'll still have your Hamilton marine chronometer that you can keep winding for a long time (they have proven to be very reliable for many years of operation). Make sure you wind it every day.

What if Time Travel is Impossible

It's possible that time travel, either to the past or the far future won't turn out to be possible. So, the discerning individual would want to be able to navigate by land, sea, or air via GPS, or using a sextant and their atomic clock, or a backup silicon chip clock, or

even just their mechanical chronometer. The TTC has you covered for any imaginable eventuality. (And, if you've spent a lot of money on your yacht or aircraft, you'd certainly want to have the absolute, ultimate, most-reliable timekeeper available.)

History of Prototypes

Cesium Breadboard Prototype

The first experimental design was constructed with a Hamilton 21 chronometer, a Microchip/Jackson Labs cesium chip-scale atomic clock (CSAC) (later used in the MCB Prototype), a ublox GPS evaluation kit (EVK-M8T), a Maxim DS3231 real-time clock (RTC) chip, and a servo mechanism to rotate the chronometer by a small amount (about one half degree of arc) following the seconds pulses from the GPS and CSAC.

This prototype was used to determine if it was possible to resonate a mechanical chronometer, how much motion would be required, and to refine the displays for time from the GPS and the RTC. A circuit was incorporated to allow re-setting the RTC from the GPS whenever desired.

Additional problems to be worked out were an automatic winding system, a backup battery array, and the rotational suspension system for the Hamilton chronometer. The circuits were constructed using multiple Arduino Nano microcontrollers, breakout boards, and solderless breadboards. The gimbals of the Hamilton chronometer were mounted to a cradle mounted on a large, thin ball bearing and rotated using a high-torque digital servo motor. Solutions to most of these problems were worked out, though reliability problems persisted with power supplies and the winding system. In addition, the full-circle ball bearing prevented the chronometer being rotated upward for convenient manual winding.

Figure 4: Cesium Time Traveler's Clock Breadboard

Winding Mechanism

The mechanism which continually winds the chronometer required considerable development. Winding the chronometer requires substantial torque. The state of wind

must be periodically measured to determine if winding is required. As the chronometer runs down, the winding input stem must be allowed to rotate backwards, so the chronometer may continue operation. Finally, provision must be made for manually winding the chronometer.

The successful winding mechanism uses a titanium-geared radio-control servo motor fitted with a drive pinion. The drive pinion is driven alternately clockwise and counterclockwise by the servo motor. The Servo Drive Pinion is constantly meshed with the Winding Rack, which is driven back and forth by the Servo Motor. The Winding Rack engages a Winding Gear. The Winding Gear rides on the Sinding Spindle, which has a square opening on its upper end to engage the winding stem of the chronometer.

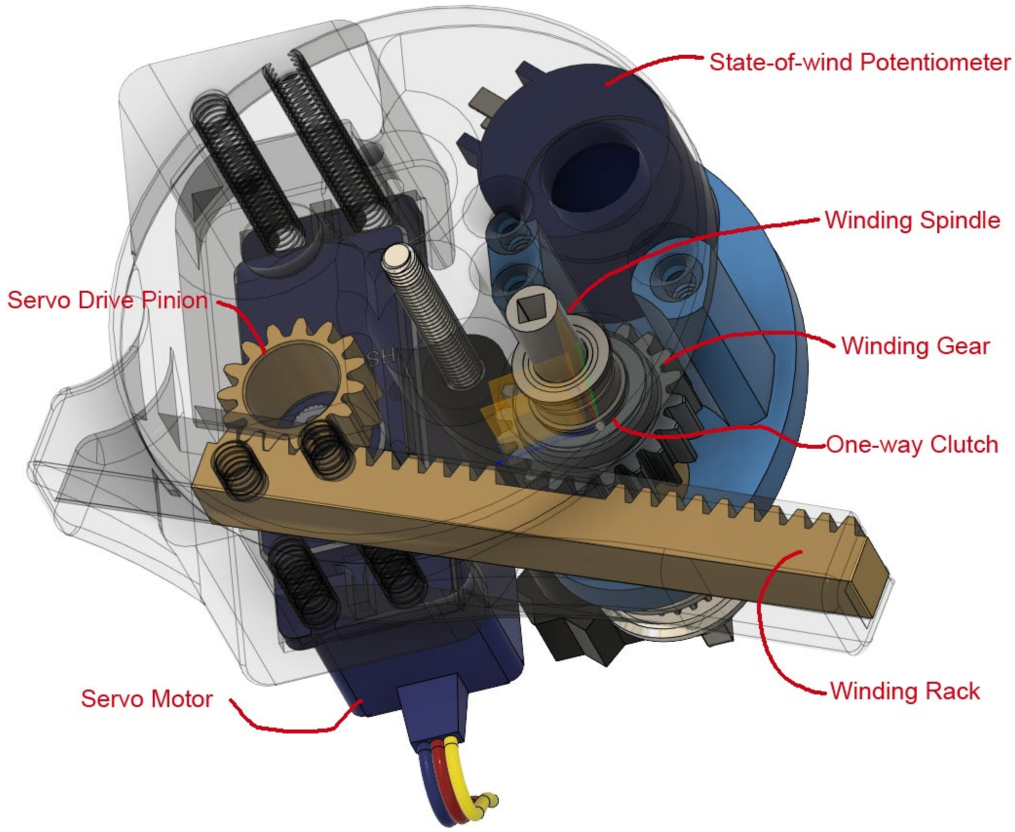
In order that the back-and-forth motion of the Winding Rack does not force the Winding Spindle backwards (which would damage the chronometer), a One-way Clutch is pressed into the Winding Gear and rides on the hardened surface of the Winding Spindle. When each winding cycle is completed, the Winding Rack is returned to its “home” position. In the home position, the rack has a portion of its teeth removed to disconnect it from the Winding Gear, allowing it to turn backwards as the chronometer unwinds.

The State-of-wind Potentiometer, coupled to the Winding Spindle by a timing belt, measures the degree to which the chronometer is currently wound. Complete winding requires approximately eight turns, so a 10-turn potentiometer is used to follow the Winding Spindle in a 1:1 ratio. This potentiometer is read by a microcontroller which controls the winding process.

The bottom end of the Winding Spindle has a 3mm square shaft protruding to allow the user to apply a manual winding key.

Every hour, the condition of the State-of-wind Potentiometer is measured by the microcontroller and the Servo Motor is actuated back-and-forth until the chronometer is fully wound.

Figure 5: Winding Mechanism



Pyramid Cesium CSACGPSDO Prototype

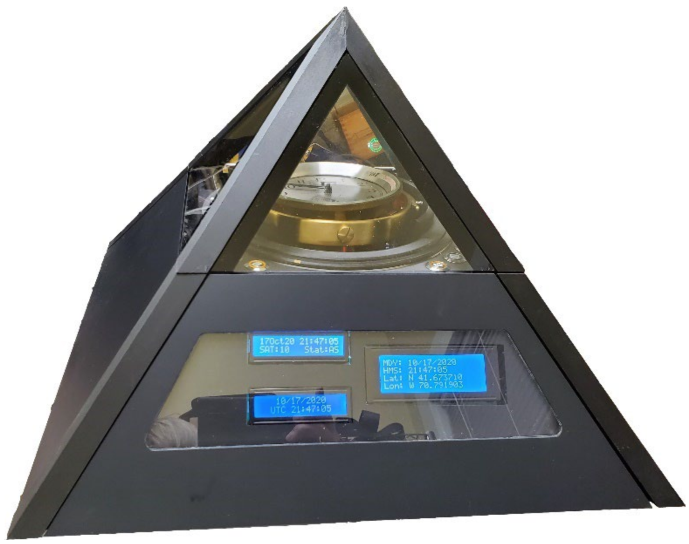
The next generation of prototypes was built in a pyramidal shape with proportions from the Great Pyramid of Giza. The bottom of the enclosure was black acrylic with a window for the electronic displays, and the upper cover was clear acrylic to allow viewing of the controls and chronometer. The thermal printer to record the natural rate of the chronometer was added to the rear panel, and backup batteries (Saft thionyl-chloride D cells) were fitted inside the base. The “tick” signal output from the mechanical chronometer needed to operate the rating circuit and printer was changed to a simple contact-closure mechanism which is available in a few of the Hamilton 21 chronometers which were made in the last century. While only a few of these exist, the mechanical contact closure is much superior to optical and audio sensors that were evaluated to pick up the “ticks” of the chronometer.

In the Pyramid Clock, the atomic reference was a Jackson Labs cesium-CSAC GPS Disciplined Oscillator module, which incorporated a cesium reference oscillator phase-locked to the GPS chip. A separate display was run from this module to display the date, time, latitude, longitude, and operational characteristics of its GPS and the CSAC. The GPS clock was a ublox EVK-M8F module, which provided date, time, longitude, and

latitude independently from that supplied by the CSAC GPS Disciplined Oscillator. The Maxim RTC system was unchanged except for software refinements.

The gimbal support and servo system were like those on the Cesium Breadboard Prototype. The problem of not being able to manually wind the chronometer without disassembling the housing remained and needed to be fixed.

Figure 6: Pyramid Time Traveler's Clock



It was found that a redundant GPS systems was not needed, because a CSAC GPS Disciplined Oscillator (either cesium or rubidium) provided date, latitude, longitude, and time from the atomic reference, maintaining accuracy to a millisecond per year.

Cube Box Rubidium Prototype

The inventor decided that the pyramid enclosure, while having an interesting appearance, was not very space-efficient, and he decided to go with a more traditional, cubical, mahogany box, like what has been traditionally used for marine chronometers, but increased in size (having more internal volume and a smaller footprint than the pyramid). The cube box had a lower section (about 2/3 of the height) that enclosed all the circuits, batteries, and chronometer. A display panel was mounted behind the chronometer, and a row of display lights and switches was placed across the front of the chronometer. The upper section of the box was hinged and latched to the lower section, covering the chronometer and controls. It allowed the user to see all the displays, switches, and chronometer through a clear window. Above the upper section was a hinged lid and latch to close the box.

In this prototype the atomic reference was a stand-alone rubidium miniature atomic clock (MAC) from Jackson Labs. This oscillator was calibrated with a GPS-disciplined reference clock before use. The 10MHz output of the MAC was connected to an input on the GPS module (a ublox EVK-M8F) to supply the chip with a precision time base to

allow the GPS to maintain accurate time during “holdover”, when a GPS signal is not available. This simpler design works as well as the cesium CSAC/GPS-Disciplined-Oscillator module, is less expensive, and is less complicated.

In the Cube Box, the chronometer gimbals were mounted on an aluminum lazy-susan bearing that was cut away at the rear; this opening allowed the chronometer to be tilted upward for manual winding. The lazy-susan bearing, however, had too much clearance between its races, resulting in unstable oscillations of the servo drive.

The chronometer-rate printer was mounted in a separate enclosure and connected by a cable to the rear panel of the box.

In addition to the GPS Antenna connection on the rear panel, SMA connectors supplied the MAC 10MHz reference frequency, the MAC 1-pulse-per second (1pps) signal, the GPS 1pps signal, and the chronometer seconds-tick signal. A push-on connector was provided for the rate printer.

Refinements needed to this design included improving the reliability of the automatic winding system, providing a more precise gimbal-support bearing, aesthetics, and reversion to a cesium-based atomic reference.

Figure 7: Cube Box Traveler’s Clock

Metal Cube Box Final Prototype

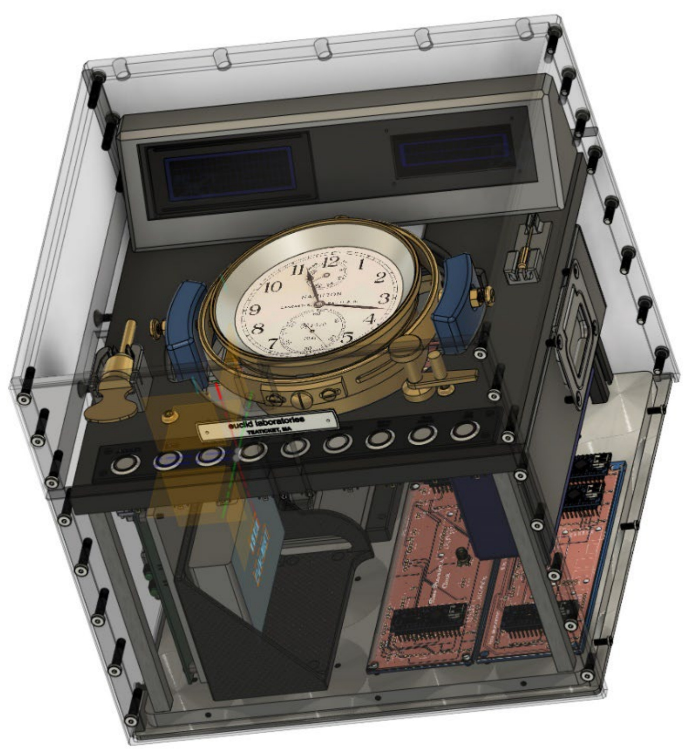
The next prototype incorporated a fully-machined anodized aluminum enclosure in place of the mahogany box following the same design and dimensions. The gimbal-

support bearing was changed from the lazy-susan bearing to a precision V-groove circular rail with four support bearing rollers; the rear part of the rail was cut away to allow the chronometer to be rotated for winding. This bearing arrangement was more precise, so the servo synchronizing mechanism performed much better.

The displays were simplified to two LCD displays: one showing the GPS date, time, latitude, and longitude and one showing date and time from the RTC. No separate display was used for the CSAC, as it operates only to supply the 10MHz precision reference frequency.

The rubidium MAC was replaced with the cesium CSAC used in the Cesium Breadboard Prototype. Otherwise, the MCB Prototype was like the Cube Box Prototype and used the same electronic hardware and firmware. The operational scheme remained with the GPS module being fed a precision 10MHz frequency reference from the CSAC to ensure long-term accuracy during holdover.

Figure 8: Metal Cube Box Time Traveler's Clock (rendered with clear case)



How the TTC Works

Marine Chronometer Advantages and Deficiencies

The Hamilton 21 Marine Chronometer represents the height of development of portable mechanical clocks for navigation. The basic design, developed by several companies in Switzerland (Zenith, Ulysse-Nardin, Ditisheim, among others) includes a

wooden box, gimbals, chronometer case, and a clockwork which incorporates a fusee mechanism for near-constant winding force as the mainspring winds down, a detent escapement, and a temperature-compensated balance wheel fitted with a helical hairspring.

When the US Navy realized the upcoming need for thousands of such chronometers in the years prior to World War II, the only company which could fill the need was Hamilton Watch Company of Lancaster, Pennsylvania. Hamilton could meet the need if the basic design of a Ulysse-Nardin chronometer was exactly copied, except for the balance wheel assembly. Hamilton had developed a better way to create a temperature-compensated balance wheel that would not require the time-consuming and laborious process of regulation that was required by the Swiss-pattern chronometers.

Figure 9: Ulysse-Nardin Marine Chronometer, Predecessor to Hamilton 21

By making the balance wheel an unbroken ring of stainless steel supported by a simple two-spoke arrangement made from Invar (a metal alloy with near-zero change in dimension with temperature change), a Hamilton could manufacture a balance with built-in temperature compensation not requiring many days of regulating. Hamilton produced about 10,000 such chronometers prior to and during the war, and these were found to be the most reliable and precise chronometers manufactured until that time.

The advantages of a mechanical, manual-wind chronometer are its reliability and trustworthiness. As long as the chronometer is wound each day, accurate time is

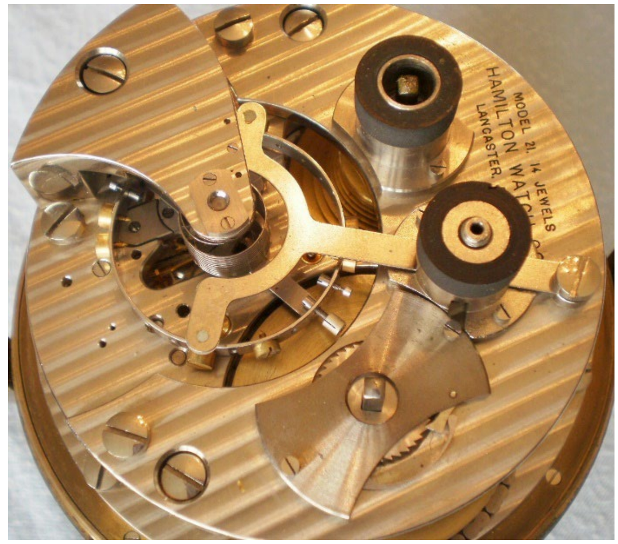
assured. Each instrument could be regulated to keep time within a second per day, and—more important—its deviation from perfect time would be a very precise value which would not change over the life of the chronometer. Each chronometer supplied to the Navy (and, also, to the US Army Corps of Engineers) came with a record telling when it was set to time as well as its measured error per day. From these data a navigator could subtract the daily error multiplied by the number of days from the currently displayed time, resulting in a very accurate “corrected” time for navigation.

Weaknesses of a mechanical chronometer include the need for continual winding; and, if the instrument is allowed to run down, then all knowledge of time will be lost. Also, while physically very robust, these instruments have to be handled with great care in order not to upset the timekeeping. On larger ships the navigator kept two or three chronometers for redundancy.

During normal operation, the TTC keeps the mechanical chronometer synchronized to GNSS or atomic precision by means of a servo-mechanical system. It has been found that a very small rotation of the chronometer every second will quickly cause the chronometer to become synchronized to that rotation, because the escapement and balance system in the chronometer become resonant with the applied mechanical rotation. It is this resonance that affords the chronometer the ability to maintain “perfect” time as long as the atomic or GNSS signals are present. If those signals are no longer present, such as if all power is lost for an extended period, the chronometer will revert to its natural rate. During normal operation, once per day, at midnight UTC, the servo synchronization is turned off so that the natural rate of the chronometer can be measured versus the atomic or GNSS standard, and that error is printed on a paper tape.

Should the electronic clock systems in the TTC be lost, the user can use these historical measurements to calculate the best time for navigation by applying the daily error to the time read on the chronometer, as was done in the past, before satellite and atomic standards.

Figure 10: Hamilton 21 Marine Chronometer



GPS Clock Advantages and Deficiencies

The various global navigational satellite systems (GNSS systems, including the US GPS, Russia's Glonass, Europe's Galileo, and China's Beidou) rely on very-high precision time keeping in order to allow a receiver to calculate its own position. Each satellite broadcasts its current time and its ephemeris (the parameters of its orbit). The receiver must then compare the times received from multiple satellites, correct for relativistic timing frame differences, and perform a complex calculation to "multilaterate" its own position on earth. In the process, the receiver also calculates the current time to a very high degree of accuracy, on the order of nano- or micro-seconds. A timing-rated receiver can provide true time accurate to within a few tens of nanoseconds.

When provided with an external frequency reference, the GNSS receiver can maintain the time ("holdover") even if satellite signals are lost. By itself, the uBlox M8F receiver has a holdover precision of 1 x 10-^{7}, or 8 milliseconds per day. If an atomic reference signal is supplied, then the holdover precision will be equal to the precision of the atomic reference signal (in the TTC, 1 x 10^{-10}, equivalent to a few milliseconds per year).

Since these satellite signals are available almost anywhere on earth, the time provided by a GNSS receiver is the time used for most scientific, civil, and navigational purposes. Why would a user need to use precise time for navigation, given that he has a GNSS receiver giving precise latitude, longitude, and altitude data? The answer is that GNSS systems can be jammed or spoofed, resulting in inaccurate location calculations. By keeping a reliable clock continually set to known good GNSS time, a navigator may use a sextant and navigational number tables to calculate his position, even if the GNSS signals are incorrect or unavailable.

The TTC can be used for navigation because it has multiple time references, including atomic, quartz, and silicon-based clocks in addition to its mechanical chronometer.

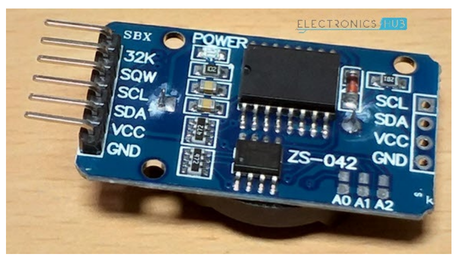
When GNSS time signals are available, the quartz, silicon, and mechanical clocks are kept synchronized to satellite time.

Silicon Clock Advantages and Deficiencies

One of the redundant clocks contained in the TTC is an integrated-circuit chip (Dallas DS3231) which contains a temperature-corrected quartz oscillator of its own and an extremely-low power microprocessor which maintains correct time, even if it's main power supply is lost, using a small backup battery. The lifetime of the backup battery is at least ten years, and it is only used when the normal power supply is not available.

This integrated-circuit clock is not as accurate as an atomic or GPS clock, but it can serve as a timing reference if all else is lost, and it is a redundant clock to supplement the other quartz, atomic, and mechanical timekeeping systems. The integrated-circuit clock in the Dallas DS3231 chip is specified to be accurate to within one minute per year; DS3231 chips used in the TTC are individually tested and calibrated to achieve significantly improved timekeeping, on the order of seconds per year.

Figure 11: Real-time Clock with DS3231 Silicon Integrated Circuit



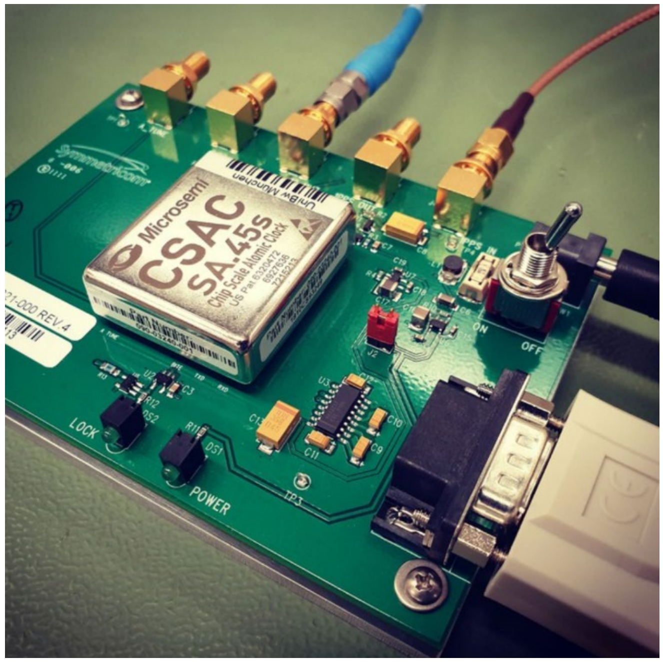
Atomic Reference Advantages and Weaknesses

TTCs use atomic frequency standards based upon the oscillations of cesium or rubidium atoms. These are the most precise reference standards available that can be used in portable equipment. The "Miniature Atomic Clock" (MAC) and "Chip-scale Atomic Clock" (CSAC) technology was developed by Jackson Laboratories.

The current state-of-the-art devices are cesium CSAC modules such as the one used in the latest MCB version of the TTC. The signal from this module, a 10 MHz reference, is supplied to the GNSS timing receiver so that if satellite signals are not available, the receiver will go into "holdover" mode with the precision of an atomic clock. The cesium CSAC modules have an accuracy of 1×10^{-10}, which is equivalent to a few milliseconds per year. In the TTC, this signal serves as the reference to not only the GNSS receiver, but also to the mechanical chronometer by way of the servo synchronization system.

Atomic clocks require continuous electrical current to maintain their accuracy. However, if power is restored after a temporary loss, the atomic clock module will re-establish its operation according to the last stored tuning data and once again begin to supply a stable reference signal to the GNSS receiver. During the time that the atomic reference is lost, the GNSS receiver will revert to its own internal quartz reference, which is precise to 1×10^{-7}, or 8 milliseconds per day.

Figure 12: Cesium Chip Scale Atomic Clock Circuit Board



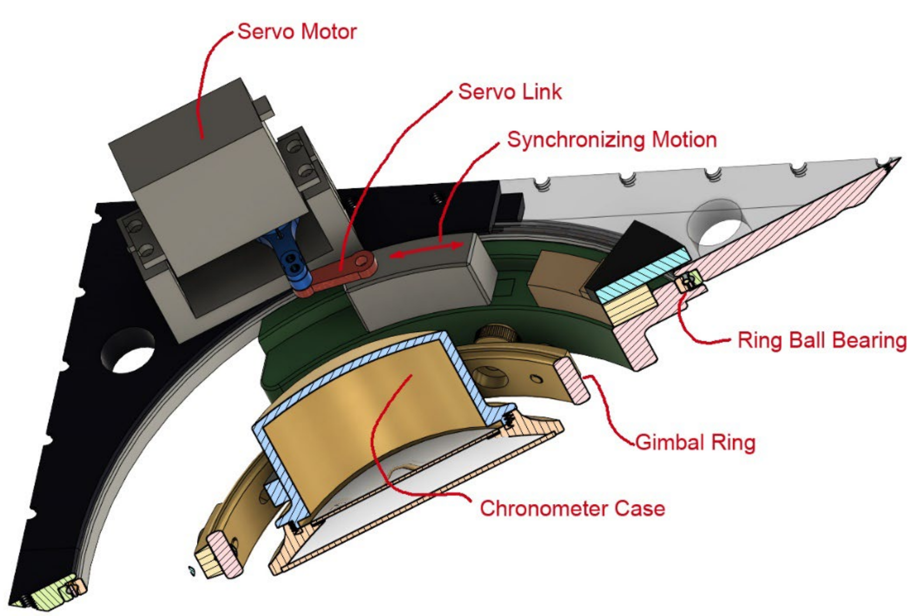
ServoSync Design Evolution

The conception of the Time Traveler's Clock includes the means by which a mechanical chronometer is kept in perfect synchronization with an atomic- or GPS-based time signal. A very small rotary motion (on the order of +/- 0.5mm) applied to the gimbal-mounted chronometer will cause the balance wheel and detent escapement to fall into resonance with that motion. Several design problems needed to be solved in order to make this system practical. A servo motor of the type used in robots and remote-control models is driven by a microcontrollers to provide a back-and-forth motion, and this motion is connected to the gimbals of the chronometer by means of a lever and a linkage.

Two problems remained: how to mount the chronometer and its gimbals in such a way that the chronometer can be rotated by this small amount; and, how to provide space for the chronometer to be tilted forward so it could be manually wound. Three successive designs were developed.

1. Ring-bearing Design:
   The first design developed to impulse the chronometer back and forth in a rotary direction used a thin-section ball bearing. A servo motor was linked to the rotary carriage with a simple linkage to transmit the back-and-forth rotary impulse to the chronometer gimbal rings. This design worked well, but the bearing, being was a complete circle, would not allow the chronometer to be tilted forward for manual winding.

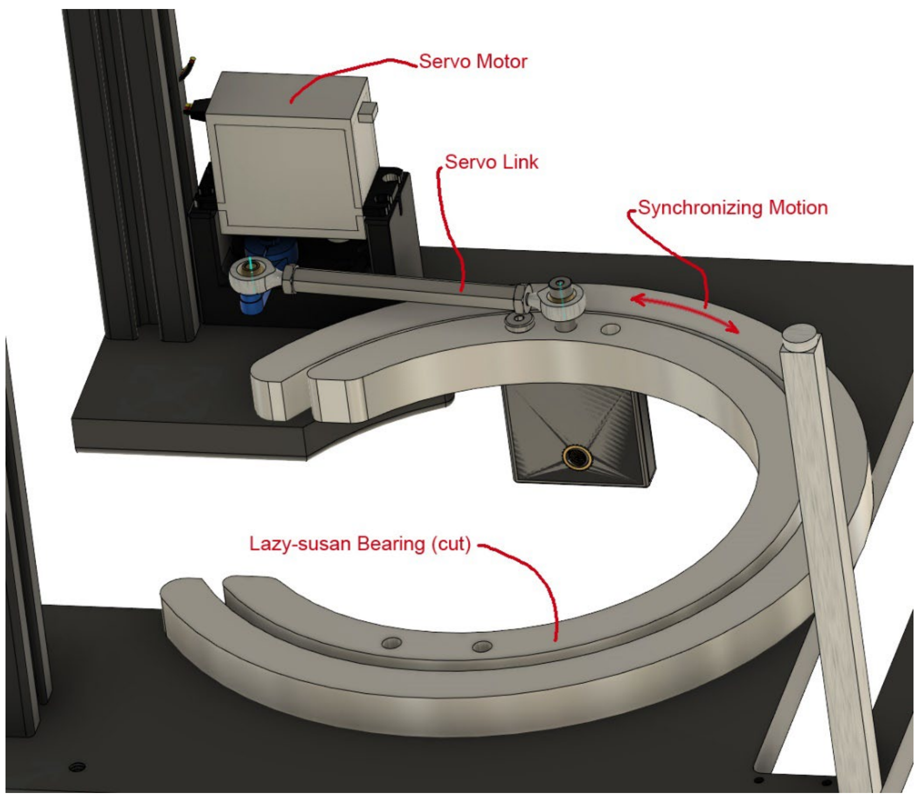
Figure 13: ServoSync Mechanism with Thin Ball Bearing Design



2. Lazy-Susan Design:

A simpler ball bearing of the type used for “lazy Susan” rotary tables was used. This bearing has cast aluminum races, steel balls, and a plastic carrier for the bearing balls. The inner and outer rings and the plastic ball carrier are cut to provide clearance for the chronometer to be tilted forward for manual winding. Again, a servo motor and linkage provides the rotary impulse motion. This design proved to be too loose to assure imparting precision motion to the chronometer.

Figure 14: ServoSync Mechanism with Lazy-susan Bearing Design



3. V-groove Circular Rail Design

The final in the “Metal Cube Box” uses a V-groove bearing arrangement in which a stainless steel ring is supported by four small, plastic-covered ball-bearings with V-grooves to match the outer periphery of the ring. The stainless steel ring is attached to the chronometer gimbals. The motion is transmitted from a servo motor via a linkage, as in previous designs. The ring is cut to allow space for the chronometer to be tilted forward for manual winding. The V-groove design solves the deficiencies of the previous designs.

Figure 15: ServoSync Mechanism with V-Groove Bearing

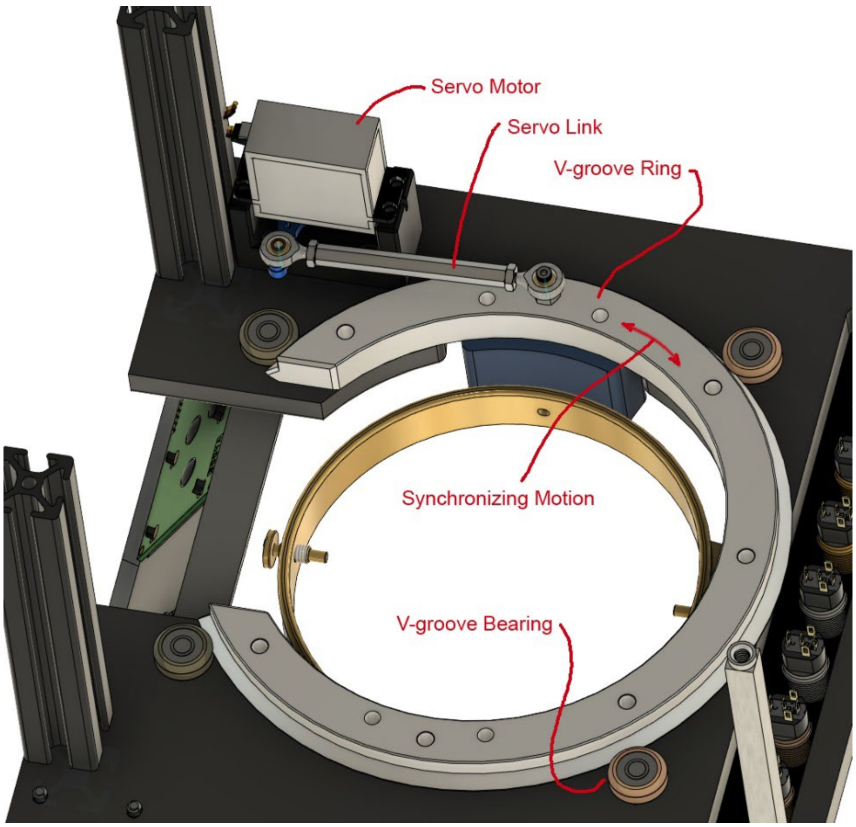


Figure 16: Time Traveler's Clock System Schematic Diagram

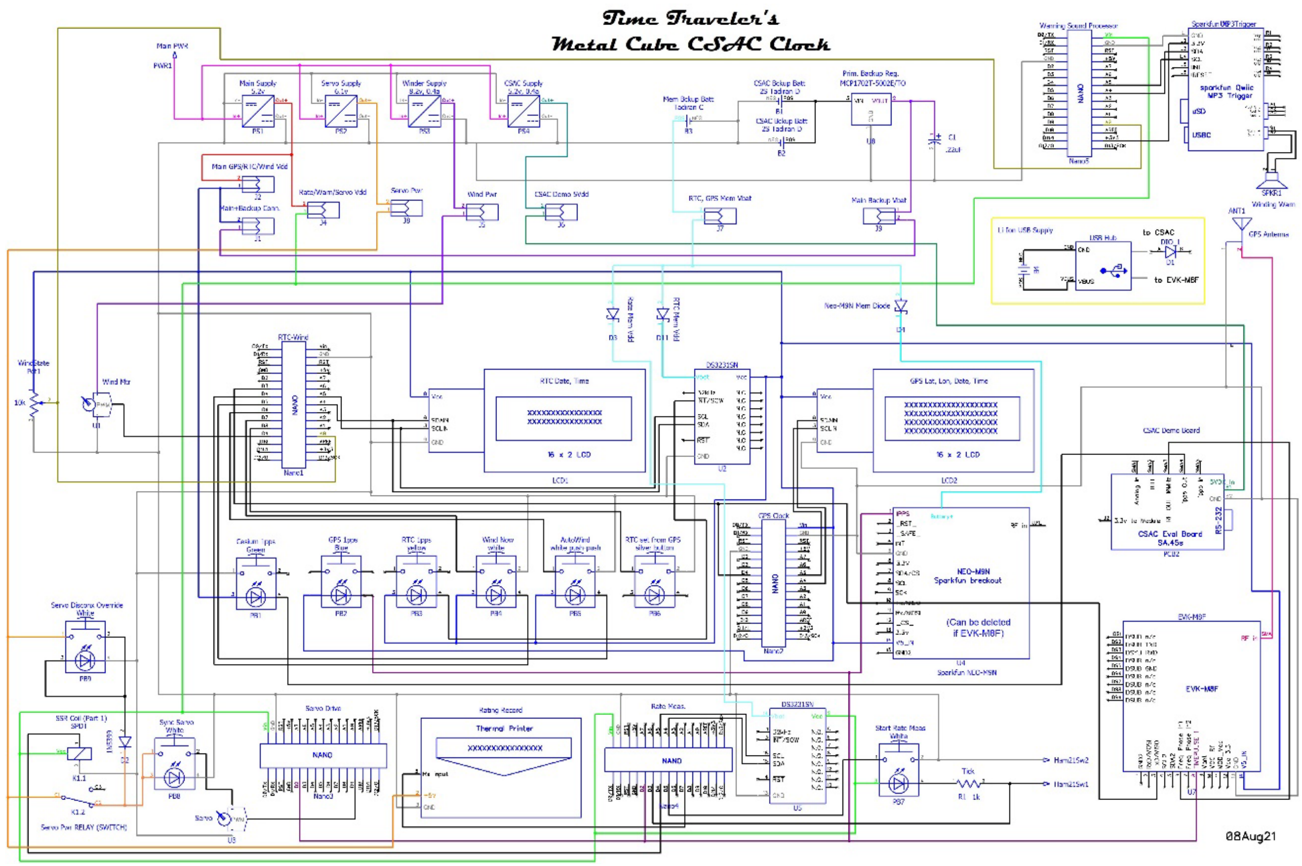
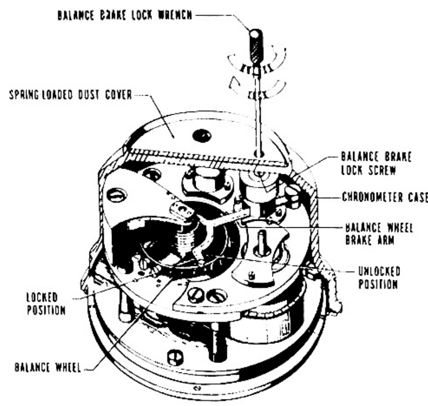


Figure 17: Hamilton 21 Chronometer Starting Instructions

STARTING INSTRUCTIONS FOR HAMILTON SIZE 85 CHRONOMETERS



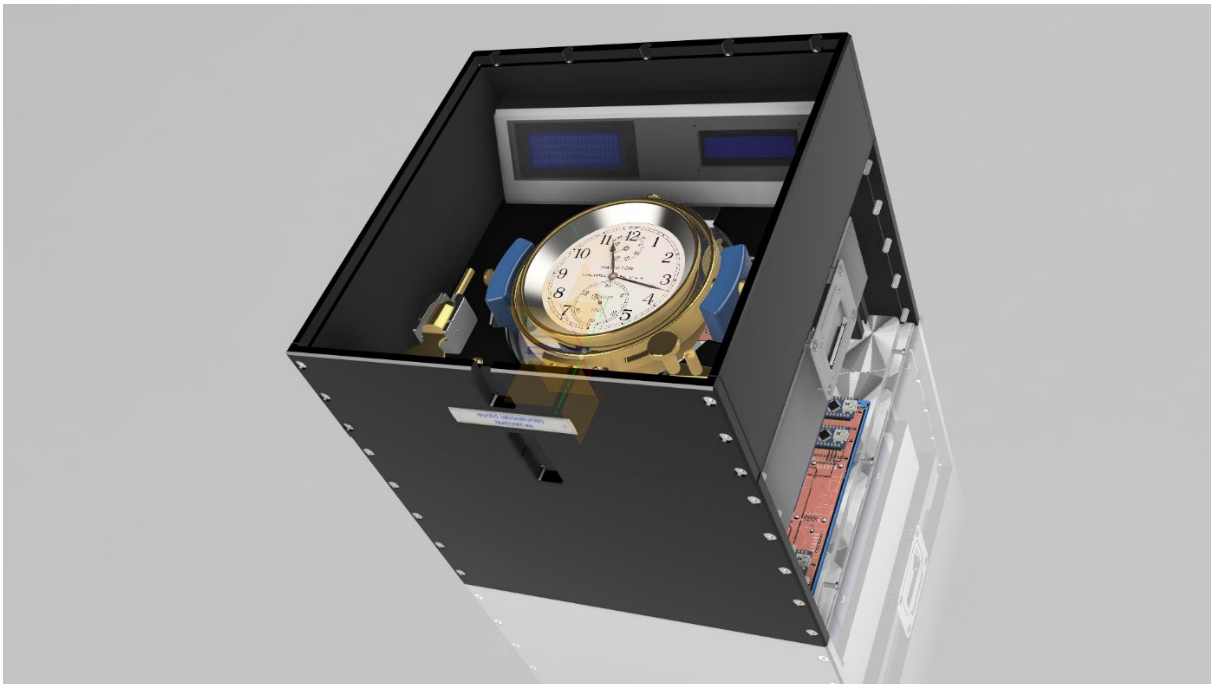
LOCKING DEVICE

After chronometer is removed from its shipping container, exercise caution and adhere to the following procedure to place in use.

1. Grasp knurled edge of glass bezel firmly, and invert instrument.
2. Insert winding key into larger of the two holes on spring-loaded dust cover. Rotate cover clockwise until winding key engages winding arbor. Fully wind chronometer.
3. Insert BALANCE BRAKE LOCK WRENCH (located in gimbal box) into the smaller hole in DUST COVER. Rotate cover clockwise until wrench engages BALANCE BRAKE LOCK SCREW (refer to illustration).
4. Rotate wrench in a fully counterclockwise direction (approximately 1½ turns) to release BALANCE WHEEL BRAKE ARM. Remove wrench and gently release dust cover.
5. Carefully restore chronometer to the dial-up position and gently unscrew glass bezel. Place winding key on square shank in center of dial to set hour and minute hands. DO NOT TURN HANDS BACKWARD (COUNTERCLOCKWISE).
6. Serious damage will result if an attempt is made to set the seconds hand. For the seconds hand to indicate correctly, instrument must be started at a specific time. Starting is accomplished by twisting instrument (approximately ¼ turn) to right or left while holding dial upright. The specific time for twisting is that instant of the minute which agrees with the stopped second hand. Correct time should be obtained from radio time signal (WWV or WWVH).
7. Replace bezel, and secure instrument in gimbals of stowage box.

NOTE: When vessels obtain instruments by shipment, replaced instruments should be packed in the same manner as those received and returned to the same pool from which the new instruments were obtained. Before packing, lock balance wheel as indicated in above sketch.

TTC Installation and Operation Manual



Installation and Connections

- What's Included
  - The Time Traveler's Clock
    1. The TTC should be set up in a place where a window is available nearby for the GPS antenna (SMA extension cables may be used if necessary).
  - Timing Printer and Supplies
    1. *Rate Error* is the average daily deviation from perfect timekeeping for a chronometer. The Printer is an optional accessory which produces a hard copy record of the native daily rate error of the Hamilton chronometer. The printer is connected to the rear panel of the TTC by means of a push-on connector. No other connection is required.
    2. The printer uses a thermal paper tape. The user will need to put in a replacement spool of tape when the tape runs out. Prior to running out, the tape will have a red stripe along its length to warn the user.
    3. Use of the printer is optional. It may be turned off by means of the power button on the Printer front panel, or it may be disconnected from the TTC.
    4. The rate error information recorded on the paper tape will be useful in the eventuality of loss of electrical power, when it will become necessary to wind the chronometer by hand and apply correction to its displayed time for navigational purposes.
  - Main Power Battery, Charger, and Connecting Cable
    1. The main power supply consists of a battery-backed uninterruptible power supply (UPS) that supplies 12V DC current to the Main 12V power connector on the rear panel. The UPS will support several hours of normal operation during a temporary power outage.
  - Backup Battery Charger
    1. An internal rechargeable backup battery provides continuous power to the atomic clock module, even if the main power supply and battery back-up is lost. This battery is powered from a secondary 12V DC power connection on the rear panel. This secondary back-up power maintains the operation of the atomic clock for several hours.
  - GPS Antenna
    1. A standard GPS antenna with SMA connector is provided that connects to a jack on the rear panel. The antenna provided supports L1 GNSS systems (GPS, Beidou, Glonass, and Galileo).
  - Internal Lithium-Thionyl Chloride Reserve Supply
    1. An internal last-reserve primary (non-rechargeable) battery consists of four D-size lithium-thionyl chloride cells, which will provide continued operation for the atomic clock and GPS receiver for up to a day after the rechargeable batteries have been depleted, or if they need to be momentarily disconnected to move the TTC. These cells should be replaced if the TTC rechargeable supplies have ever been allowed to fully run down. The shelf life of these cells is in excess of ten years.

Figure 18: Rear Panel Connections

- Connections
  - Main Power Input
    1. Plug the UPS DC supply charger into an AC mains outlet (100-240V).
    2. Plug the 12V DC output from the UPS into the jack on the left side of the rear panel labeled "Main 12VDC". Screw the plug down to secure it to the jack.
  - Backup Battery Charger Input
    1. Plug the backup battery charger supply into an AC mains outlet (100-240V).
    2. Plug the 12V DC output from the backup battery charger main supply into the second jack from the left labeled "Aux 12VDC" on the rear panel. Screw the plug down to secure it to the jack.
  - GPS Antenna Input
    1. Place the GPS antenna in a position where it has a good view of the sky. This may be outside or it may be in a window (preferably facing south).
    2. Connect the GPS antenna cable to the jack labeled "GPS Ant." Screw the connector down finger-tight.
  - Rate Error Printer Output
    1. Connect the cable from the Thermal Printer to the jack labeled "Printer" on the rear panel by turning it so the red dots align and pushing it on. No tightening is required. The printer cable may be removed by grasping its knurled sleeve and pulling straight out.
    2. Using the Printer is optional and will not affect the operation of the TTC.
  - Chronometer 1pps Tick Output
    1. The "Chrono" output supplies the signal from the contact points in the Hamilton chronometer. This output is a 5V logic-level signal that goes to ground at the beginning of each second, except for the 59th second.
    2. The Chrono output may be used for diagnostic purposes but does not affect the TTC operation.
  - Cesium 10MHz Output
    1. This output, labeled "10 MHz", may be used for other purposes, such as providing a reference signal to another instrument. Its use is not required for TTC operation. This output comprises a "Stratum 0" reference signal.
  - CSAC 1pps Output
    1. This output is a one-pulse-per-second output from the EVK-M8F GNSS receiver.
    2. The 1pps signal initiates the rotational motion by the Servo Synchronization function which keeps the Hamilton chronometer locked to the Atomic and GNSS time. This output comprises a "Stratum 0" one-pulse-per-second signal .

- Winding and Setting the Chronometer
    - The chronometer is provided fully wound but “stopped” by an internal friction element which prevents the balance from rotating. The starting procedure is detailed on the instruction panel in the lid of the TTC. *(See Figure 13)*
    - It is important to follow the Starting Instructions precisely, or damage can result to the chronometer. NEVER TURN THE HANDS COUNTER-CLOCKWISE!
    - The chronometer can be set using the GPS display on the TTC once it has acquired satellite signals (satellite lock is indicated by the latitude and longitude being shown on the GPS display). Once “seconds” of the GPS display is one second ahead of the second hand on the chronometer, the chronometer can be started by quickly rotating the entire TTC clockwise and back and forth. The minutes and hours can be set once the chronometer is running. NEVER TURN THE HANDS COUNTER-CLOCKWISE!

Normal Operations

- Daily Operation
    - Reading Times from the Display Panel
        1. The GPS display (4 lines of 20 characters) shows Month:Day:Year, Hours:Minutes:Seconds (UTC Time), Latitude, and Longitude.
        2. The Real-time Silicon Clock display (2 lines of 20 characters) shows Month:Day:Year and Hours:Minutes:Seconds. This display is completely independent from the other timekeeping systems and serves as a backup and confirmation of proper operation. The time displayed on the Real Time Clock display may be several seconds different from the UTC time shown on the GPS display.
            - There is a provision to re-set the Real Time Clock from the GPS system, if desired, by pushing the red “Set RTC” button, but this should be done only if there is a reliable GPS time signal (latitude and longitude are being displayed).
            - Pressing the “Set RTC” button when there is not a reliable GPS time may result in inaccurate setting of the Real Time Clock.
    - Reading Time and Winding Reserve from the Chronometer
        1. The Hamilton chronometer has traditional hour, minute, and seconds hands. The time may be set to UTC (recommended) or to any other time zone.
        2. Setting the chronometer is a manual operation and should not be required unless power is lost for more than a day and the chronometer is allowed to run down. During extended power outages, it is necessary for the operator to manually wound the chronometer (see instructions below).
        3. The state of winding is indicated by the “UP – DOWN” dial immediately below the “12” on the dial. Normally, while the autowinder is operating, the indicator should be approximately at the 8-hour position. If allowed to wind down, the hand will move clockwise, indicating how long it has been since the

chronometer was fully wound. After the hand goes past "48 hours", the chronometer will stop and will need to be restarted and re-set.

4. Any time the chronometer stops because of not being wound, follow the "Starting Instructions" carefully and do not shock the chronometer. Otherwise, damage may be done to the sensitive escapement mechanism in the chronometer.

- Time-keeping Verification
  - If the GPS display, RTC display, and chronometer dial agree, then it is assured that the TTC is indicating accurate time.
  - If the chronometer stops, but there is still GPS time displayed (and it agrees within a few seconds to the Real Time Clock), the chronometer may be restarted according to the "Starting Instructions."
  - If Power is lost for less than 12 hours, the TTC should restart by itself and indicate accurate time.
  - If power is lost for over 24 hours but less than 48 hours, and the backup batteries are depleted, the TTC may be re-initialized using the instructions above, as though it were new from the factory, although the chronometer should still be operating and will not need to be reset.
  - If power is lost for over 24 hours, the chronometer should be manually wound to keep it running and indicating mechanically-accurate time.
  - If power is lost for an extended period of time, and GPS is not available once the power is returned, the only displays which will indicate accurate time will be the Real Time Clock display (within a few seconds of accurate time) and the mechanical chronometer.

Figure 19: Hamilton 21 Chronometer Starting Instructions

- Servo Controls
  - ServoSync

The system which keeps the Hamilton chronometer synchronized with the GPS and Atomic time reference is called ServoSync. Synchronization is achieved by a small rotary impulse motion delivered to the chronometer by a servo motor, triggered by the 1pps signal from the GPS circuit. The motion is small, on the order of one-half millimeter, but can be felt by resting a finger on the ring surrounding the chronometer. The ServoSync function is controlled by the "ServoSync" button on the top panel. One push turns the function on, and another push turns it off. When active, the button is lit green.

- Rate Atomic and Rate Error Measurement

    1. The “Rate Atomic” button is a push-on/push-off button. It is lit green when the “Rate Atomic” function is engaged. Engaging this function prevents the ServoSync motion being turned off at midnight when the timing of the chronometer is measured. If “Rate Atomic” is engaged, the rate measured by the rating system will be the rate of the chronometer while being impulsed by the ServoSync system (hence, the rate error should be close to zero).
    2. In order to conserve paper, there is no need to operate the Printer when the Rate Atomic function is engaged.
    3. The Rate Atomic button may be engaged during normal operations, but it is recommended that at least once per month the function be turned off and the Printer turned on, so historical rate error data may be gathered for possible future use. Rate error measurement occurs at midnight UTC each day.

- Rate Now

    “Rate Now,” illuminated yellow, is a momentary control button which causes the rate-error measurement system to go into action whenever desired. Provided the Rate Atomic control is turned off, the chronometer will go into stand-alone operation without ServoSync, and its rate will be measured against the GPS/Atomic reference; the result will be printed on the Printer exactly as it would be at midnight.

- Set RTC

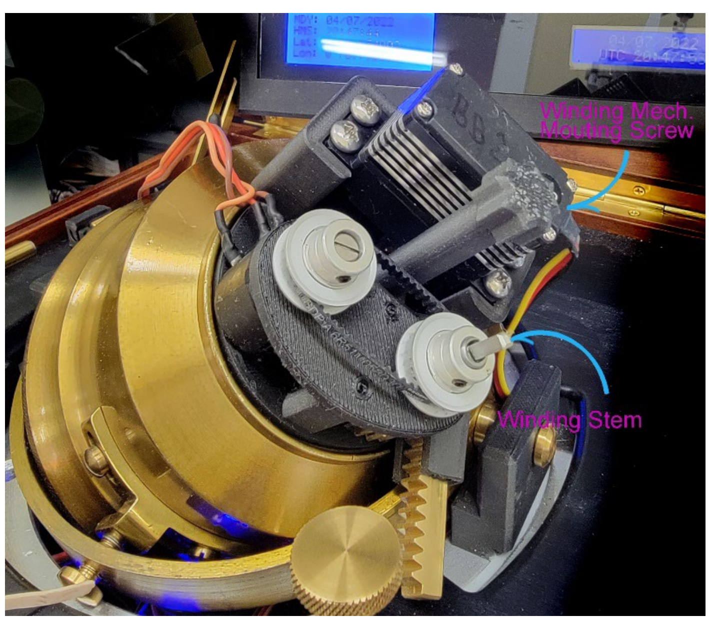
    “Set RTC” button, illuminated red, is used only in the case when it is desired to reset the silicon Real Time Clock to GPS time. This should only be done if a reliable GPS signal is present (latitude and longitude are shown on the GPS display). It may take several presses of the button to set the RTC precisely to GPS time. (Note: the Set RTC button should only be pressed when the GPS time reads between zero and forty seconds.)

- Winding Controls
    - Wind Now
        1. Pressing the Wind button will cause the winding mechanism to cycle. In order to wind a chronometer that has run down, it would be necessary to press the Wind button several times.
    - AutoWind
        1. If AutoWind is engaged (push-on/push-off, lit white when turned on) the chronometer will be wound to the preset value (usually 8 hours from full wind) every hour, on the hour. During normal operation of the TTC, this function should be turned on.
    - Manual Winding
        1. If the AutoWind function is not working (because of loss of power or failure of the mechanism), the chronometer should be manually wound at least once per day.

2. Procedure for manual winding:
   - Push the lower latch and tilt the upper portion of the case backwards to access the controls and the chronometer.
   - Remove the GPS and RTC Display by lifting it up and backwards (it is held on curved mounting pins). After it is removed, it may be rested on the back of the opened upper case. Be careful not to put tension on the flat, flexible cables which go to the display.
   - Manually rotate the chronometer, carefully, upwards from back to front, about 180 degrees. This will allow access to the winding mechanism.
   - Remove the winding key from its nest on the TTC control panel.
   - Place the winding key onto the small square winding stem on the winding mechanism. (If the AutoWind mechanism has been removed, the key goes directly into the hole surrounding the chronometer's winding stem.)
   - Turn the winding key counter-clockwise to wind the chronometer. There is a ratcheting mechanism in the key to prevent forcing the winding stem in the wrong direction. It will take 17 half-turns of the winding key to fully wind the chronometer if it has completely wound down. Each day of running will require about half that amount of winding.

     Once the "stop" is felt to prevent further winding, remove the key and return the chronometer to its normal horizontal position. Then, replace the GPS and RTC Display and close the upper part of the case.

Figure 20: Chronometer Tilted for Manual Winding



- Other Control Panel Indicators and Buttons
    - "Atomic" blinks green once per second, powered by the 1pps signal from the cesium clock.
    - "GPS" blinks blue once per second, powered by the 1pps signal from the GPS receiver; it should be in sync with the Atomic light (the blue Atomic light blinks quickly exactly as the blue GPS light turns off).
    - "Silicon" blinks yellow once per second, powered by the Real Time Clock. Typically, the RTC light is out of sync with the GPS and Atomic lights, because it operates completely independently and has lower precision than GPS or Atomic.
- Printer
    - Normal Operation
        1. The Printer can be connected to the rear panel, and its power button turned on (it will be lit white when on).
        2. At midnight UTC the ServoSync function will be disabled (unless the "Rate Atomic" button is turned on), allowing the chronometer to run at its natural rate.
        3. For a period of 35 minutes, measurements are collected of the timing of the "ticks" of the chronometer measured against the GPS/Atomic timing reference. The errors are printed out, along with an average daily rate error on the Printer. These data may be used to diagnose the operation of the chronometer and as a correction for navigation using chronometer time and sextant according to normal navigational procedures.
- Metal Cube Case Operation and Alternate Configurations
    - The Cube Case may be opened by pressing the upper latch and lifting the lid from the upper section of the case to view the displays and chronometer. The lid may be removed entirely by lifting straight up at the back (the hinges will unplug from the upper-case section).
    - The upper-case section may be opened by pressing the lower latch and lifting it up to allow access to the controls or for manually winding the chronometer. The upper section may be removed entirely by lifting straight up at the back, like the case lid. It is not recommended to leave the upper case open, which would allow dust and debris to enter the interior of the TTC.
    - There is a cooling fan on the rear panel which draws in air through a filter to keep the interior clean and cool. The fan is very quiet and is always on as long as there is Main Power.

Maintenance Operations

- Warm Resetting the Electronics
    - If the displays are frozen or show corrupt data, they may be reset by turning off the Main 12V DC Power (easily done by turning off the battery-backed 12V supply.
- Cold Reset After Long-term Power Loss
    - Cold resetting the electronics should only occur if AC or DC power is lost for approximately two days. In this case, the battery-backed 12V supply (Main 12V) will

most likely will have been turned off and its 12V DC Power output will need to be turned back on.

- Once AC and DC power is available:
  1. The Main 12V battery-backup supply should start recharging its battery
  2. the electronics and displays should turn back on
  3. The internal battery which powers the GPS and CSAC atomic clocks will start charging
  4. The GPS should find satellites and re-establish latitude, longitude, and time
  5. The CSAC atomic clock will resume operation and once again provide a precise reference signal to the GPS system.
  6. Winding will resume if AutoWind is enabled, and the chronometer will be wound to its normal condition (approximately 8 hours on the state-of-wind indicator)
- The chronometer, if fully run down, will need to be reset and restarted, as is described above in "Winding and Setting the Chronometer".

- Changing the Printer Paper
  - When the paper tape supply is nearing its end, there will be a red stripe visible on the printed tape. At this time additional paper rolls should be obtained. It is recommended to use archival-type thermal paper to avoid fading of the printed results over time.
  - Open the front cover of the thermal printer by pulling down on the center tab.
  - Remove the old paper spool and insert the new spool with the paper tape running out the bottom of the spool.
  - Close the front cover of the printer.
  - Operation of the paper feed can be verified by pressing the small "feed" button on the lower left of the printer.
- Locking the Chronometer for Storage or Shipment
  - If the TTC (or the Chronometer by itself) will be shipped or moved by any means other than hand-carry, the chronometer must be stopped. The bottom of the chronometer may accessed as described above in "Manual Winding".
  - Once the bottom of the chronometer is visible, the AutoWind system must be removed by unscrewing the knurled black thumbscrew in its center.
  - With the AutoWind system removed, a small Allen hex-drive screw is visible. It should be turned clockwise to lock the chronometer's balance wheel. The screw can be turned with the L-shaped Allen wrench provided and should only be turned "finger-tight" to stop the balance wheel.
  - After stopping the balance wheel, the AutoWind mechanism may be placed back onto the bottom of the chronometer, secured by the thumbscrew, and the chronometer returned back to its normal face-up position.
  - After the chronometer has been stopped, engage the gimbal ring lock by loosening the knurled thumbscrew and turning the brass lever in the near-right corner of the control panel to engage the slot in the gimbal ring. Once the lever is engaged in the slot, re-tighten the knurled thumbscrew to hold it in place.

Figure 21: Gimbal Locking